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LETTER

One Approach to the Star-Formation History Inferred from the GRB Lag–Luminosity Relation

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Abstract

The distances of about thirty gamma-ray bursts (GRBs) are known. The most remote one is at $z \sim 4.5$, and the remaining more dimmer GRBs are supposed to be more remote. If we can estimate the distances for the dimmer GRBs, their distances should be much beyond $z \sim 4.5$. Two independent studies to estimate their distances were previously conducted. One was based on the variability–luminosity relation, and the other was based on the lag–luminosity relation. However, these relations can apply only for a very limited range of luminosity. In this paper, we introduce the viewing angles and use a new lag–luminosity relation by Ioka and Nakamura (2001, ApJ, 554, L163), which is capable of explaining the luminosity of the nearest GRBs. By applying the new relation, we infer the star-formation history out to $z \sim 4$. Our result shows an increasing trend of star-formation out to $z \sim 4$. However, the lag–luminosity relation itself is still a matter of debate, and thus this work is a tentative approach. For example, we have used only eight known GRB distances. Our result should be checked and calibrated by future data with Swift, observing more distant GRBs.

Key words: cosmology: early universe — gamma-rays: bursts — stars: formation

1. Introduction

Since the discovery of an X-ray afterglow of GRB 970228 with BeppoSAX in 1997 (Costa et al. 1997) and the optical identification of the GRB (van Paradijs et al. 1997), the long controversy concerning the GRB distance was solved and the GRBs were proved to be very remote (van Paradijs et al. 2000). There are about thirty GRBs which have known distances and known host galaxies.[1] The most remote one is at $z \sim 4.5$, and their mean is $z \sim 1$ (Frail et al. 2000). Limited to the BATSE data base, there are eight GRBs with known distances. The GRBs with known distances were rather bright. Therefore, the more dimmer GRBs should be more remote. If the distances to the dimmer GRBs were known, we could estimate the star-formation history at the extremely early universe just after the first star formations. The popular and most common idea for the origin of GRBs is the collapse of a super-massive star at the time of the formation of a black-hole (collapsar or hypernova models; Woosley et al. 1999; Paczyński 1998). Because the life of these massive stars is very short, GRBs have a capability to estimate the first stage of massive star formation during the early universe. However, to estimate the GRB rates, we should know the distances to the dimmer or more remote GRBs. Two independent methods to estimate the distances were proposed before. One was the pioneering work by Fenimore and Ramirez-Ruiz (2000), using the variability–luminosity relation. The other was the lag–luminosity relation by Norris et al. (2000). Although the number of GRBs is very limited, and also these relations are still a matter of debate, GRBs are the only method at present to estimate the star-formation rate out to $z \sim 10$, observationally.

Giving a luminosity to a GRB, we estimate the distance using the observed gamma-ray flux with BATSE (Paciesas et al. 1999). However, the linearity of the previous methods was poor, and also the lag–luminosity relation was applicable only for a very limited range of luminosity. For example, it was very difficult to include GRB 980425, which was the nearest GRB (Norris et al. 2000; Fenimore, Ramirez-Ruiz 2000; Schaefer et al. 2001; Lloyd-Ronning et al. 2002; Reichart et al. 2001). In this paper, we introduce viewing angles in order to understand the lags, which were first introduced by Ioka and Nakamura (2001). They interpreted that the larger lags were due to larger viewing angles. This idea can naturally explain the nearest case of GRB 980425, which appears to be the most reliable distance indicator at present.

The star formation rates (SFRs) and the deep-field searches of galaxies during the early universe were studied using many methods. For example, number counts of galaxy in UV and in optical with HST, and also in the sub-millimeter range with SCUBA, were conducted (Madau et al. 1996; Ferguson et al. 2000; Hughes et al. 1998; Chapman et al. 2003). However, due to the limited sensitivities of these observations, and also the inevitable absorptions, these results sometimes require large corrections to estimate the true SFR at more than $z \sim 2$. In fact, the Madau-plot in 1996 gave only the lower limits (Madau et al. 1996). A summary of the most recent results has been published out to 6.6 with SUBARU, but this

[1] See the web page of J. Greiner at ⟨http://www.mpe.mpg.de/~jcg/grbgen.html⟩.

also gave lower limits beyond $z \sim 4$ (Kodaira et al. 2003). However, SFRs inferred from GRBs do not require any correction for the absorption, and also have a capability to reach out to $z \sim 10$. These advantages of GRBs were first considered in earlier works by Totani (1997) and Wijers et al. (1998). In this paper, we report on the SFRs up to $z \sim 4$, inferred from GRBs, and compare our result with previous studies, which have reported a decreasing trend in the SFR at the deeper universe beyond $z \sim 3$. In the summary, we also mention the weakness of the present method.

2. Estimating Distances

We explain the procedures for estimating the distances to the dimmer GRBs in this section. First, we assume the new lag–peak-luminosity relation by Ioka and Nakamura (2001) as a distance indicator. We do not explain the details of the Ioka–Nakamura model in this paper. For more details of the model, refer to the paper by Ioka and Nakamura (2001). However, we should mention one important result which we use for estimating the distances in figure 1. This relation shows a good fit to all of the eight GRBs with known distances in the BATSE catalog, including GRB 980425. This is the advantage of our work compared with previous studies. The previous studies assumed a straight line, which could explain the data of only a limited range (Norris et al. 2000).

First, the lags of the 298 GRBs in the 4th BATSE catalog (Paciesas et al. 1999) were estimated for the observer frame, using data in the public archive with 64 ms time resolution in two energy bands of 25–55 and 110–320 keV, cross-correlating each channel. We used only 298 GRBs in this work, which have a good S/N for estimating these lags. This selection roughly corresponds to the GRBs, which are brighter than $\sim 1.5\,\mathrm{photon\,cm^{-2}\,s^{-1}}$ above 25 keV. For dimmer GRBs, it is difficult to estimate proper lags. We derive the lags in units of 64 ms in time resolution for each GRB. This caused a discrete population of the peak luminosity but this did not cause trouble in the next step. In future work, we will try to use dimmer GRBs. The details of the process used for estimating the distances, except for the new lag–peak-luminosity relation, are the same as in the papers by Fenimore and Ramirez-Ruiz (2000) and by Schaefer et al. (2001). First, we calculated the lag for a burst and second we estimated the peak-luminosity from the lag–peak-luminosity relation, and then calculated the luminosity distance,

$$L = 4\pi D^2 P_{256} \langle E \rangle.$$

Here, D is the luminosity distance for $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{m} = 0.3$, $\Omega_\Lambda = 0.7$, P_{256} is the BATSE peak flux for the 256 ms time resolution from 50 to 300 keV in units of $\mathrm{photon\,cm^{-2}\,s^{-1}}$, and $\langle E \rangle$ is the average energy of the photons for the E^{-2} spectrum (Band 1997), which corresponds roughly to $1.72 \times 10^{-7}\,\mathrm{erg\,photon^{-1}}$ in conversion. These conversion factors are the same, which were used in the paper by Schaefer et al. (2001). However, because this is the distance in the observer frame ($z = 0$), we corrected the lag using the derived distance and again estimated the luminosity and repeated this process a few times (iteration) to estimate the true distance. A plot of the correlation (after iterations) between the luminosity distances and the peak fluxes is shown in figure 2. The discrete population in luminosity is the result of the discrete time resolution of the BATSE data in estimating the lags.

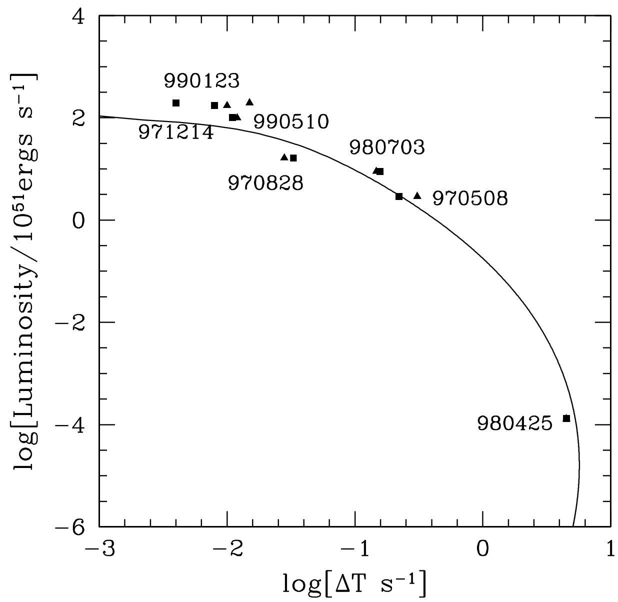

Fig. 1. Lag–peak-luminosity relation which was proposed to explain all of the BATSE GRBs with the known distance, including GRB 980425 by Ioka and Nakamura (2001), together with the observed luminosities by Norris et al. (2000). The lags are at the rest frame of the GRBs. This figure was adopted from Ioka and Nakamura (2001)

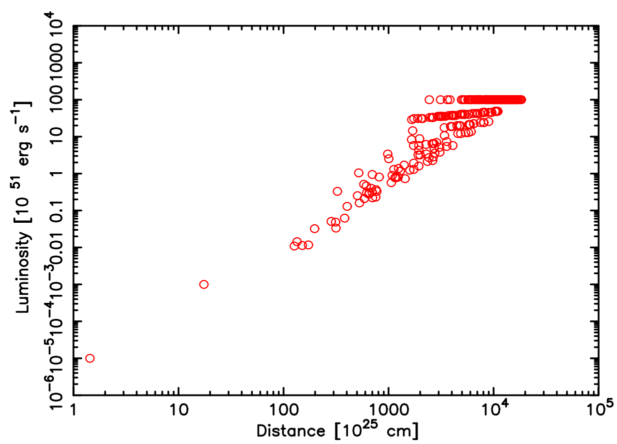

Fig. 2. Plots of the derived GRB luminosity distances against the peak-luminosities after iterations. Discrete populations in luminosity at the large luminosity are due to the discrete values of the estimated lags in units of 64 ms time resolution.

3. Estimating SFR

Using the 298 GRBs distribution of the distances in figure 2, we then derived the burst rates of GRBs in units of the comoving volume and time. First, we divided the data shown in figure 2 into seven groups depending on their distances, and then produce seven cumulative $\log N$–$\log L$ curves as shown in figure 3. To estimate the range of luminosity for the 7th group

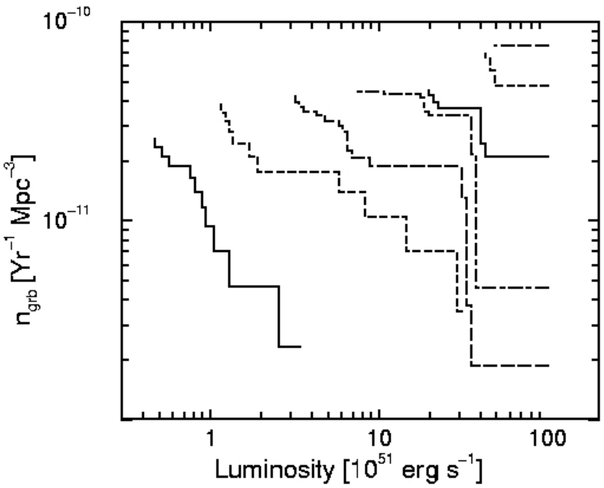

Fig. 3. GRBs, plotted in figure 2, divided into seven groups. This figure shows the $\log N - \log L$ plots, after correcting for the comoving volume and the time dilation for each group. There are clear discrepancies between them in each $\log N$ value at the same luminosity.

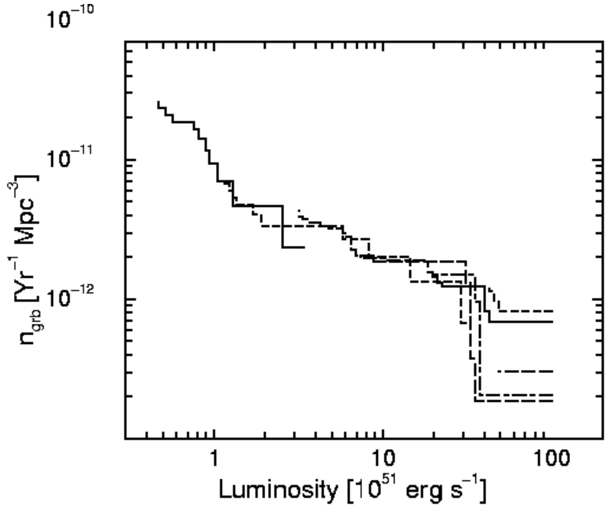

Fig. 4. Smoothed $\log N - \log L$ curve, in which the data of figure 3 are placed into one smoothed line. After this rearrangement, there is no discrepancy in the $\log N$ value at the same luminosity for each group. These corrections or shift values are proportional to the star-formation rate.

in the plot, we used the fact that Ioka and Nakamura's (2001) formula has a luminosity saturation of about $2 \times 10^{53}\,\mathrm{erg\,s^{-1}}$. Figure 3 shows discrepancies in the $\log N$ values at the same luminosity.

To correct the discrepancies in $\log N$, we shifted each $\log N - \log L$ group to be placed into one smooth curve, as shown in figure 4. This is simply because the GRBs with the same luminosity should have the same rate. The factors of the shift for placing the groups to one smooth curve are the differences in the GRB rates in the unit comoving volume and time. Plots of the correction factors are shown in figure 5. Figure 5 also shows the errors of this process. The errors were estimated using the event number (N) of each step of $\log N - \log L$. We treated the number N to follow the Poisson distribution, and also included the propagation of errors to make one smooth curve shown in figure 4. However, the errors to place data into a smooth curve are not purely statistical, but rather systematic, as shown in figure 5. We do not consider the errors of the model universe used nor the errors of the lag–peak-luminosity relation by Ioka and Nakamura (2001). This is the first and simple step to estimate the order of magnitude of SFRs inferred from GRBs.

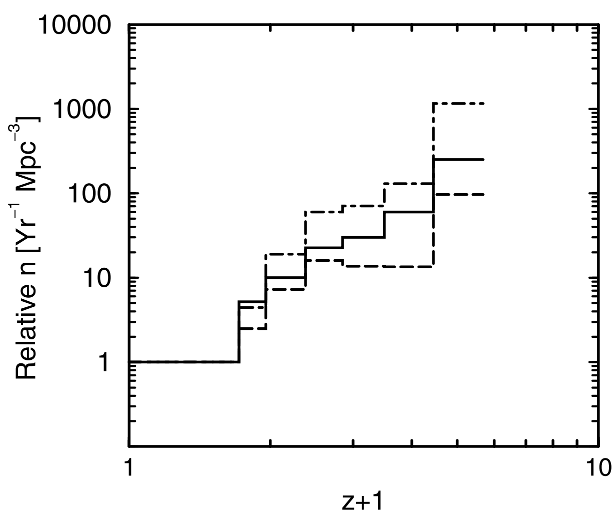

Fig. 5. Relative GRB event rates per comoving volume and comoving time (solid line) derived from Ioka and Nakamura's (2001) formula and from figure 3. The errors (dashed and dash-dotted lines) were estimated from the number N and also from the propagation of errors in placing seven curves into one smooth curve.

4. Summary and Conclusion

GRBs are the most violent and brightest explosions known in the universe. We certainly detected a GRB at $z \sim 4.5$, and most of the much dimmer GRBs are probably out to $z \sim 10$ and more. More sensitive future satellites, like Swift, are expected to be detected GRBs out to $z \sim 100$ (Gehrels 2000). On the other hand, a recent report of the WMAP survey observations in the micro-wave band revealed that our universe is 13.7 billion years old (Kogut et al. 2003), and that 2 billion years after the explosion or big-bang, the first star formation of super-massive stars, which might be progenitors of GRBs, took place (Barkana, Loeb 2001; Woosley et al. 1999). If these scenarios are true, more frequent GRB explosions are expected at an earlier phase of the universe. Soon after the first identification of cosmological GRBs, theoretical studies on GRBs and SFRs were made by Totani (1997) and Wijers et al. (1998). Although GRBs with known distances are very limited, we report on SFRs, observationally introducing the most reliable lag–peak-luminosity relation based on the viewing-angle corrections by Ioka and Nakamura (2001).

In figure 6, we show the known SFRs together with our result. The best-known SFRs are adopted from the results of the Hubble deep field (Ferguson et al. 2000) and from Fenimore and Ramirez–Ruiz (2000) based on GRBs. The most common understandings concerning the observed SFR

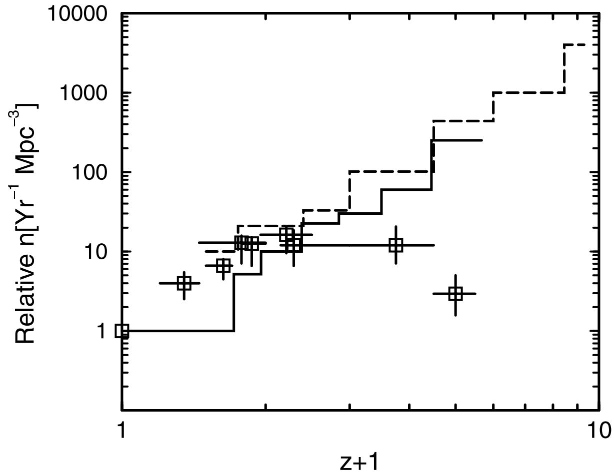

Fig. 6. Relative GRB rates per comoving volume and comoving time (present work; thick step line) derived from $\log N - \log L$ curves together with the known star-formation rates for the Hubble deep field (Ferguson et al. 2000, crosses) and from the pioneering work by Fenimore and Ramirez-Ruiz (2000, broken step line). The relative star-formation rates derived from GRBs show no saturation in the star-formation rate.

histories are an increasing trend towards $z \sim 2$ and saturation (or even a decreasing trend) beyond this limit. The SFR, which is sometimes called a Madau plot, also showed the same decreasing trend (Madau et al. 1996). The most recent result by Kodaira et al. (2003) also shows the decreasing trend. However, the results derived from GRBs increase beyond this limit, and show no turn over. The three independent studies by Fenimore and Ramirez–Ruiz (2000), Schaefer et al. (2001), and the present work are consistent with each other and show no turn over. We should note the reasons for these discrepancies between the SFRs derived from GRBs and other wave bands. The first point is that the SFRs in UV and in optical bands sometimes require large corrections for the absorption, which reduce the SFR at a distant place. The second is that the SFR inferred from GRBs is observing only the SFR of a super-massive object evolving into a collapse which forms a black-hole. However, the SFRs derived from the sub-mm wave band might trace only the SFR in the dusty environment.

In fact, although GRBs do not require any correction for the absorption, GRBs still have serious problems and difficulties, which we should mention. The first is that GRBs are really beaming, and thus we require corrections for the solid angle to estimate the true SFRs. However, we do not know the degree of beaming, which depends on the luminosity. The second point is that we did not include any cosmological evolution of the luminosity. The last difficulty is that, not to say, the lag–luminosity relation itself is still a matter of debate. In spite of these difficulties in deriving SFRs from GRBs, GRBs might be the only realistic method at present, for estimating SFRs experimentally out to $z \sim 10$. In the near future, we should calibrate our results by detecting GRBs out to $z \sim 10$ in the era of Swift, which will be launched in 2004.

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